Optimal Design of Service Overlay Networks

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***Abstract*— Service Overlay Networks (SONs) are currently one of the most promising architectures envisioned to provide end-to-end Quality of Service guarantees in the Internet, without requiring significant changes to the underlying network infrastructure. A SON is an application-layer network operated by a third-party Internet Service Provider (ISP) that owns a set of overlay nodes, residing in the underlying ISP domains, interconnected by overlay links.**

The deployment of a SON can be a capital-intensive investment, and hence its planning requires careful decisions, including the overlay nodes' placement, the capacity provisioning of overlay links as well as of access links that connect the end-users to the SON infrastructure.

In this paper we propose two novel optimization models for the planning of Service Overlay Networks which aim to select the number and positions of overlay nodes, as well as the capacity reserved for each overlay link, while taking into account in an accurate way traffic routing. The first model minimizes the SON installation cost while providing full coverage to all network's users. The second model maximizes the SON revenue by further choosing which users to serve, based on the expected gain, and taking into consideration budget constraints that the SON operator could specify.

We provide the optimal solutions of the proposed problem formulations on a set of realistic-size instances and discuss the effect of different parameters on the characteristics of the planned networks.

***Index Terms*: - Service Overlay Networks, Network Design, Mathematical Models.**

I. Introduction

The Internet has experienced a tremendous growth in its size and complexity in the last few years; it connects today thousands of Autonomous Systems operated by different Internet Service Providers (ISPs), companies and universities.

The Internet was designed to provide mainly a best-effort delivery service; however, Internet users often require services that need end-to-end Quality of Service (QoS) guarantees and traverse multiple domains. Although several approaches have been proposed in the literature to support QoS in the Internet, like Integrated Services [1] and Differentiated Services [2], such approaches are far from being widely deployed since they require significant changes to the underlying Internet infrastructure.

Service Overlay Networks (SONs) have recently emerged as one of the most promising architectures envisioned to provide end-to-end Quality of Service guarantees in the Internet, while leaving the underlying Internet infrastructure unchanged [3], [4], [5], [6], [7].

A SON is an application-layer network built on top of the traditional IP-layer networks. In general, the SON is operated by a third-party ISP that owns a set of overlay nodes residing in the underlying ISP domains. These overlay nodes perform service-specific data forwarding and control functions, and are interconnected by virtual overlay links which correspond to one or more IP-layer links [3].

The service overlay architecture is based on business relationships between the SON, the underlying ISPs, and the users. The SON establishes bilateral service level agreements with the individual underlying ISPs to install overlay nodes and purchase the bandwidth needed for serving its users. On the other hand, the users pay the SON for using its overlay services via a service contract [3], [7]. To assure the bandwidth for the SON, the underlying ISPs have several technical options. They can either lease a transmission line to the SON, use bandwidth reservation mechanisms, or create a separate Label Switched Path if MPLS [8] is available in their networks.

Evidently, the deployment of Service Overlay Networks can be a capital-intensive investment. It is therefore imperative to develop network design tools that consider the cost recovery issue for a SON. The main costs of SON deployment include the overlay nodes installation cost and the cost of the bandwidth that the SON must purchase from the underlying network domains to support its services.

Very few previous works consider the problem of topology design for Service Overlay Networks [7], [9], [10]. All these works, however, assume that the number and location of overlay nodes are pre-determined, while the overlay nodes placement is a critical issue in the deployment of the SON architecture. Furthermore, these works assume that a full coverage of all traffic demands must be provided, while the main goal of a SON provider would be to maximize its revenue by choosing which users to serve based on the expected income. Finally, previous works often do not impose bounds on overlay links capacities, assuming that the underlying ISPs will always be able to provide bandwidth to the SON.

In this paper we tackle all the above issues by proposing two novel overlay network design models that select the optimal number and position of overlay nodes, as well as the capacity reserved for each overlay link, while taking into account in an accurate way traffic routing.

The first model minimizes the network installation cost while providing full coverage to all network's users. The second model maximizes the SON revenue by further choosing which users to serve to make its operation profitable, eventually considering a budget constraint that the SON operator could specify to limit its risks in the deployment of the overlay network.

The problems are NP-hard but they can be solved to the optimum for realistic-size instances. We provide optimal solutions for a set of instances and investigate the impact of different parameters on the SON design problem: number and installation cost of overlay nodes, bandwidth costs, traffic demands and SON provider's budget.

The paper is structured as follows: Section II discusses related work. Section III introduces the proposed overlay network design models. Section IV discusses numerical results that show the effect of different parameters on the characteristics of the planned network. Finally, conclusions and directions for future research are presented in Section V.

II. Service Overlay Networks: Topology Design Issues

Several works have appeared in the literature with the purpose of providing optimal topology design in different contexts, such as wired backbone networks [11], [12], [13], [14], wireless networks [15], [16], and recently Service Overlay Networks [7], [10], [9], [17], [18].

An adaptive topology design framework for SONs is presented in [7] to assure inter-domain QoS, and a set of heuristics is proposed to solve the least-cost topology design problem. A similar problem is investigated in [10], where end-systems and overlay nodes are connected through ISPs that support bandwidth reservations; simulated annealing is used as heuristic to provide solutions for large-sized networks. Another set of heuristics for SON design is proposed in [9]. These heuristics aim to construct an overlay topology maintaining the connectivity between overlay nodes under various IP-layer path failure scenarios. However, all these works formulate the design problem considering full coverage of all traffic demands and assuming that locations of overlay nodes are given and the underlying ISPs are always able to provide resources to the SON.

Reference [17] deals with dynamic topology construction to adapt to the topology changes of the underlying network. An architecture for topology-aware overlay networks is proposed to enhance the availability and performance of end-to-end applications by exploring the dependency between overlay paths. Several clustering-based heuristics for overlay node placement and a routing mechanism are introduced.

The problem of overlay servers placement is addressed in [18] to design an overlay network allowing the maximization of the number of unicast and multicast connections with deterministic delay requirements. Unlike our current work, the authors do not consider links costs in the network design problem.

In summary, the above cited techniques are less general than our current work since they assume that the number and location of overlay nodes are pre-determined; furthermore, they provide full coverage of all network users without considering the SON revenue maximization issue. Finally, they assume that there are no capacity constraints on overlay links. In our work, on the contrary, we take into consideration all these issues in the formulation of the overlay network design problem. In addition, we introduce a budget constraint in one of our models to limit the economic risk that the SON operator can face when deploying its network.

III. Service Overlay Network Design Models

A common approach to the network design problem is to consider feasible positions of traffic concentration points in the service area (Test Points, TPs), which generate traffic towards one or more Destination Nodes (DNs), and feasible positions where overlay nodes can be installed (Candidate Sites, CSs) [11]. The placement of TPs, DNs and CSs depends on the traffic distribution and on the underlying network topology. Although the concept of *test point* is distinguished from *end-user* (formally, the end-user is the traffic generation agent that is placed in a TP), we will use the two terms as synonyms throughout the paper. *Destination nodes* can represent both terminal nodes or access points to other networks.

Let $S = 1, \ldots, m$ denote the set of CSs, $I = 1, \ldots, n$ the set of TPs, and $D = 1, \ldots, p$ the set of destinations.

The cost associated to installing an overlay node at CS j is denoted by c_j^I; c_{jl}^B denotes the cost for the SON operator to buy one bandwidth unit between CSs j and l from the underlying ISPs, and c_{ij}^A is the access cost per bandwidth unit required between TP i and CS j; finally, c_{jk}^E represents the cost per bandwidth unit for the traffic transmitted on the egress link between CS j and destination node $k \in D$.

The traffic generated by TP i towards destination node k is given by the parameter d_{ik}, $i \in I, k \in D$. The maximum capacity that can be reserved by the SON operator between CSs j and l on the overlay link (j, l) is denoted by u_{jl}, $j, l \in S$, while the maximum capacity of the access link of CS j is denoted by v_j, $j \in S$.

According to TPs, DNs and CSs geographic location and the underlying physical topology, the following connectivity parameters can be calculated.

Let a_{ij}, $i \in I, j \in S$ be the test point coverage parameters:

$$a_{ij} = \begin{cases} 1 & \text{if TP } i \text{ can access the SON through an} \\ & \text{overlay node installed in CS } j \\ 0 & \text{otherwise} \end{cases}$$

Similarly, let e_{jk}, $j \in S, k \in D$ denote destination nodes coverage parameters:

$$e_{jk} = \begin{cases} 1 & \text{if CS } j \text{ can be connected with destination node } k \\ 0 & \text{otherwise} \end{cases}$$

Obviously, both a_{ij} and e_{jk} are related to the distance between TP i or DN k, respectively, and CS j.

Finally, let b_{jl}, $j, l \in S$ denote the connectivity parameters between two different CSs, which may depend on the proximity of the overlay nodes j and l in the underlay network, as well as on the agreements between the SON and the different ISPs.

$$b_{jl} = \begin{cases} 1 & \text{if CS } j \text{ and } l \text{ can be connected with an overlay link} \\ 0 & \text{otherwise} \end{cases}$$

Decision variables of the problem include TP assignment variables x_{ij}, $i \in I, j \in S$:

$$x_{ij} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to CS } j \\ 0 & \text{otherwise} \end{cases}$$

overlay nodes' installation variables z_j, $j \in S$:

$$z_j = \begin{cases} 1 & \text{if an overlay node is installed in CS } j \\ 0 & \text{otherwise} \end{cases}$$

destination assignment variables w_{jk}, $j \in S, k \in D$ (if $z_j = 1$, w_{jk} denotes if j is connected to destination node k):

$$w_{jk} = \begin{cases} 1 & \text{if CS } j \text{ is connected to destination node } k \\ 0 & \text{otherwise} \end{cases}$$

connection variables y_{jl}, $j, l \in S$:

$$y_{jl} = \begin{cases} 1 & \text{if there is an overlay link between CS } j \text{ and } l \\ 0 & \text{otherwise} \end{cases}$$

and finally flow variables f_{jl}^k which denote the traffic flow routed on link (j, l) destined to destination node $k \in D$. The special variables f_{jk} denote the traffic flow on the egress link between CS j and destination node k.

Given the above parameters and variables, we propose two different Service Overlay Network design formulations: the first, called Full-Coverage SON Design model (FCSD), minimizes the total network cost while assuring full coverage of all end-users. The second formulation, called Revenue-Maximization SON Design model (RMSD), maximizes the total network revenue, choosing which users to serve based on the revenue generated by their subscription to the SON services and the cost necessary to cover them.

A. Full-Coverage SON Design Model

The Full-Coverage SON Design model (FCSD) minimizes the total network cost while assuring full coverage of all network users.

$$Minimize \sum_{j \in S} c_j^I z_j + \sum_{j,l \in S} \sum_{k \in D} c_{jl}^B f_{jl}^k + \\ + \sum_{i \in I, j \in S, k \in D} c_{ij}^A d_{ik} x_{ij} + \sum_{j \in S, k \in D} c_{jk}^E f_{jk} \quad (1)$$

$$s.t. \sum_{j \in S} x_{ij} = 1, \forall i \in I \quad (2)$$

$$x_{ij} \leq z_j a_{ij}, \forall i \in I, j \in S \quad (3)$$

$$\sum_{i \in I} d_{ik} x_{ij} + \sum_{l \in S} (f_{lj}^k - f_{jl}^k) - f_{jk} = 0, \forall j \in S, k \in D \quad (4)$$

$$\sum_{k \in D} f_{jl}^k \leq u_{jl} y_{jl}, \forall j, l \in S \quad (5)$$

$$\sum_{i \in I, k \in D} d_{ik} x_{ij} \leq v_j, \forall j \in S \quad (6)$$

$$f_{jk} \leq u_{jk} w_{jk}, \forall j \in S, k \in D \quad (7)$$

$$y_{jl} \leq z_j, \forall j, l \in S \quad (8)$$

$$y_{jl} \leq b_{jl}, \forall j, l \in S \quad (9)$$

$$w_{jk} \leq e_{jk} z_j, \forall j \in S, k \in D \quad (10)$$

$$x_{ij}, z_j, y_{jl}, w_{jk} \in \{0, 1\}, \forall i \in I, j, l \in S, k \in D \quad (11)$$

The objective function (1) accounts for the total Service Overlay Network cost, including installation costs and the costs related to the connection of overlay nodes, users' access and egress costs.

Constraints (2) provide full coverage of all TPs, while constraints (3) are coherence constraints assuring respectively that a TP i can be assigned to CS j only if an overlay node is installed in j and if i can be connected to j.

Constraints (4) define the flow balance in node j for all the traffic destined towards node k. These constraints are the same as those adopted for classical multicommodity flow problems. The term $\sum_{i \in I} d_{ik} x_{ij}$ is the total traffic generated by the assigned TPs destined towards destination node k, $\sum_{l \in S} f_{lj}^k$ is the total traffic received by j from neighboring nodes, $\sum_{l \in S} f_{jl}^k$ is the total traffic transmitted by j to neighboring nodes, and f_{jk} is the traffic transmitted towards the destination node k.

Constraints (5) impose that the total flow on the link between overlay nodes j and l does not exceed the capacity of the link itself (u_{jl}). Constraints (6) impose for all overlay nodes that the ingress traffic serviced by such network device does not exceed the capacity of the link used for the access, whilst constraints (7) force the flow between node j and the destination node k to zero if node j is not connected to k. The parameter u_{jk} represents the maximum capacity of the egress link between the installed overlay node j and destination node k.

Constraints (8) and (9) define the existence of an overlay link between CS j and CS l, depending on the installation of nodes in j and l and the connectivity parameters b_{jl}. Constraints (10) are coherence constraints assuring that a CS j can be connected to a destination node k only if an overlay node is installed in j and if k can be connected to j. Finally, constraints (11) are the integrality constraints for the binary decision variables.

Obviously, the above model is NP-hard since it includes the set covering and the multicommodity flow problems as special cases.

B. Revenue-Maximization SON Design Model

The Revenue-Maximization SON Design model (RMSD) maximizes the total network revenue, choosing which users to serve based on the revenue generated by their subscription to the SON services and the cost necessary to the SON provider to cover them.

The objective function (1) is therefore changed as follows:

$$Maximize \sum_{i\in I, j\in S, k\in D} g_i d_{ik} x_{ij} - \{\sum_{j\in S} c_j^I z_j + \\ + \sum_{j,l\in S}\sum_{k\in D} c_{jl}^B f_{jl}^k + \sum_{i\in I, j\in S, k\in D} c_{ij}^A d_{ik} x_{ij} + \sum_{j\in S, k\in D} c_{jk}^E f_{jk}\} \quad (12)$$

where $g_i, \forall i \in I$, represents the income per bandwidth unit that the SON operator obtains covering Test Point i. Here we assume for simplicity that the price paid by the $i-th$ user is proportional to the amount of traffic the user introduces in the SON, $\sum_{k\in D} d_{ik}$, with g_i being the proportionality coefficient, but some general pricing models can be easily accounted for.

Constraint (2) is changed as follows, while all the other constraints are the same as in the FCSD model:

$$s.t. \sum_{j\in S} x_{ij} \le 1, \forall i \in I \quad (13)$$

With such formulation, the SON operator maximizes the total network revenue, obtained subtracting the total income, achieved by covering a subset of the Test Points, to the total cost necessary to deploy an overlay network satisfying the users' requirements. Note that, differently from constraint (2) in the FCSD model, in this formulation constraint (13) does not impose full coverage of all TPs.

The Service Overlay Network planner may be required to specify a certain cost budget to limit the economic risks in the deployment of its network. To this end, the RMSD formulation can be easily modified to account for cost limitations. With B the budget, this can be done simply by adding the following constraint:

$$\sum_{j\in S} c_j^I z_j + \sum_{j,l\in S}\sum_{k\in D} c_{jl}^B f_{jl}^k + \\ + \sum_{i\in I, j\in S, k\in D} c_{ij}^A d_{ik} x_{ij} + \sum_{j\in S, k\in D} c_{jk}^E f_{jk} \le B \quad (14)$$

IV. NUMERICAL RESULTS

In this section we test the sensitivity of the proposed models to different parameters like the number of candidate sites and test points, the traffic demands, the installation costs as well as the revenue obtained by covering end-users and the SON operator's budget.

To this end, we have implemented a topology generator which considers a square area with edge equal to 1000 m, and randomly extracts the position of m Candidate Sites (CSs), n Test Points (TPs) and p Destination Nodes (DNs). The area is divided into N Internet Service Providers (ISPs); for sake of simplicity in this paper we consider $N = 25$ ISPs obtained dividing the whole area into $L \times L$ squares, with $L = 200$ m.

We assume that each TP and DN can be connected to a CS only if the CS is at a distance not greater than 100 m from the TP or DN. As for the connectivity parameters between different CSs, we assume that each CS can be directly connected with an overlay link to any other CS (i.e., $b_{jl} = 1, \forall j, l \in S$); this allows our models to investigate all possible link configurations to find the optimal overlay topology.

The cost matrix for bandwidth (c_{jl}^B) is then generated. If CSs j and l belong to the same ISP, we assume that c_{jl}^B is fixed and equal to 1 monetary unit per Mb/s. On the other hand, if CSs j and l belong to different ISPs, c_{jl}^B depends on the peering agreements between such ISPs. For the sake of simplicity, we assume that in this case c_{jl}^B is a random variable uniformly distributed between $C/2$ and $3C/2$, with C being equal to $\frac{L_{jl}}{L}$, that is the distance between j and l (L_{jl}) divided by the width of an ISP domain (L), i.e. 200 m with the above settings.

If not specified differently, the installation cost of an overlay node is equal to 10 monetary units. As for the access and egress cost, we assume they are fixed and equal to 1 monetary unit per Mb/s.

The maximum capacity that can be reserved between CSs j and l on the overlay link (j, l) u_{jl}, $j, l \in S$ is set equal to 50 Mb/s, as well as the maximum capacity of the access link of CS j, v_j, $j \in S$. The capacity of the egress links connecting overlay nodes to destination nodes is $u_{jk} = 100$ Mb/s, for all $j \in S$ and $k \in D$.

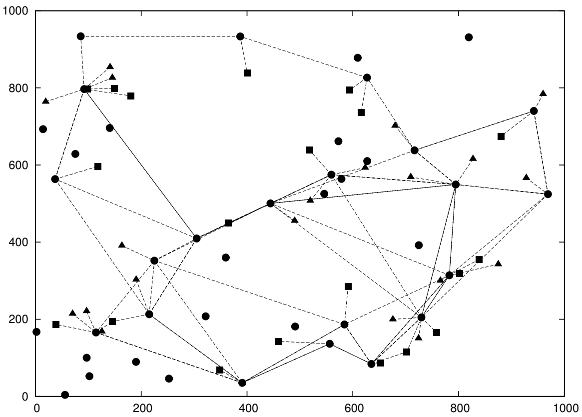
Obviously, all these assumptions do not affect the proposed models which are general and can be applied to any problem instance and network topology. We plan in the future to extend our analysis considering more complex random topology generators and real ISP topologies when available.

All the results commented hereafter are the optimal solutions of the considered instances obtained formalizing the proposed models in AMPL [19] and solving them with CPLEX [20] using workstations equipped with an Intel Pentium 4 (TM) processor with CPUs operating at 3 GHz, and with 1024 Mbyte of RAM. For each network scenario, the results are obtained averaging each point on 10 random instances.

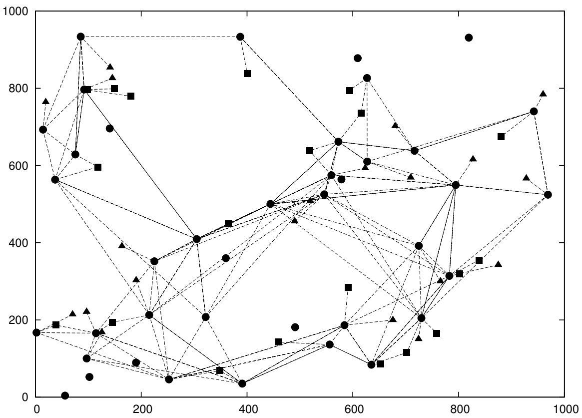
a) Effect of the Traffic Demands

We first consider the Full-Coverage SON Design model in a network scenario with $n = 20$ TPs and $p = 20$ DNs. Each test point offers the same amount of traffic d_{ik} to all destination nodes.

Figure 1 reports an example of the planned networks when applying the FCSD model to the same instance with $m = 40$ candidate sites and with two different requirements on the end-user traffic, $d_{ik} = 500$ kb/s and $d_{ik} = 1$ Mb/s for all TPs and DNs. CSs, TPs and DNs are represented with circles, triangles and squares, respectively. As expected, increasing the traffic demands forces the model to install a higher number of overlay nodes and links to convey the traffic towards the destination nodes.



(a) 500 kb/s



(b) 1000 kb/s

Fig. 1. Sample SONs planned by the FCSD model with increasing traffic demands (500 and 1000 kb/s). The number of TPs and DNs is 20, while the number of CSs is 40.

Table I analyzes the characteristics of the solutions of the FCSD model in the same scenario when varying the number of candidate sites. For each couple (m, d_{ik}) the Table reports the number of installed overlay nodes (N_R) and links (N_L), the total network cost and the processing time to get the optimal solution.

Two main results come from the observation of the Table: first, the very same effect of traffic increase observed in Figure 1 is evident also on averaged results; in fact, the number of installed nodes and links increases when increasing the traffic demands.

Second, for a given traffic value, increasing the number of CSs (m) increases the solution space; as a consequence, the model favors the solutions providing connectivity that have a lower impact on the network cost, which in turn decreases with m.

TABLE I

SOLUTIONS PROVIDED BY THE FCSD MODEL WITH 20 TPS AND 20 DNS.

d_{ik}=500 kb/s

m	N_R	N_L	Cost	Time (s)
30	18.9	146.6	997.9	49.7
40	19.3	148.5	987.0	203.4
50	18.6	141.6	972.8	4188.8

d_{ik}=1000 kb/s

m	N_R	N_L	Cost	Time (s)
30	21.1	167.7	1803.5	11.6
40	20.5	155.7	1636.7	80.8
50	19.9	148.2	1621.0	2616.3

We further consider a variation of this network scenario with $n = 100$ TPs and only one Destination Node, which can be seen as acting like a concentrator point or access point towards other networks.

The results are shown in Table II for different m and d_{ik} values, and they are in line with the observations reported above. Note that in this case the processing time to obtain the optimal solutions is almost negligible.

TABLE II

SOLUTIONS PROVIDED BY THE FCSD MODEL WITH 100 TPS AND 1 DN.

d_{ik}=500 kb/s

m	N_R	N_L	Cost	Time (s)
30	24.3	124.3	430.6	0.046
40	24.2	124.2	426.8	0.196
50	24.1	124.1	421.4	0.766

d_{ik}=1000 kb/s

m	N_R	N_L	Cost	Time (s)
30	24.4	124.4	617.2	0.049
40	24.5	124.5	609.8	0.263
50	24.4	124.4	600.7	0.774

b) Effect of the Cost

We then vary the overlay nodes' installation cost, considering a scenario with $n = p = 20$ TPs and DNs and $m = 50$ CSs. The solution, and in particular the number of installed nodes and links, intuitively depends on the ratio β between the overlay nodes' installation cost and the bandwidth reservation cost.

Table III reports the results obtained when varying the parameter β for different values of the offered traffic d_{ik}. The results reported in the Table show that if the cost for installing an overlay node decreases with respect to the bandwidth reservation cost, the proposed model tends to install more overlay nodes.

c) Effect of the Gain parameter

We then evaluate the Revenue-Maximization SON Design model, considering a scenario with 20 TPs, 20 DNs and $m = 40$ CSs. We assume that the gain per bandwidth unit that the

TABLE III

SOLUTION PROVIDED BY THE FCSD MODEL WITH 20 TPS AND DNS, 50 CSS AND VARIABLE COST RATIO β

	d_{ik}=500 kb/s		d_{ik}=1000 kb/s	
β	N_R	N_L	N_R	N_L
10	18.6	141.6	19.9	148.2
1	31.2	207.0	34.9	221.5
$1/5$	40.1	232.2	43.3	249.7
$1/10$	42.8	236.8	44.0	250.9

SON operator obtains for serving an end-user (the parameter g_i in the objective function (12)) is a random variable with average equal to G and a uniform distribution between $G/2$ and $3G/2$, with G ranging between 0 and 0.01 monetary units per Mb/s.

Figure 2 shows the number of end-users covered by the SON as a function of G. Evidently, for small G values, the SON is not profitable enough to cover any of the end-users; as G increases, the SON covers more end-users, eventually all of them. Similar results have been observed with $m = 30$ and $m = 50$ CSs.

Table IV reports, for the same scenario, the total number of installed nodes and links, the network revenue (i.e., the value of the objective function (12)), the total network cost and processing time, as a function of G.

Note that when G increases, the planned network covers more end-users, and as a consequence it comprises more overlay nodes and links.

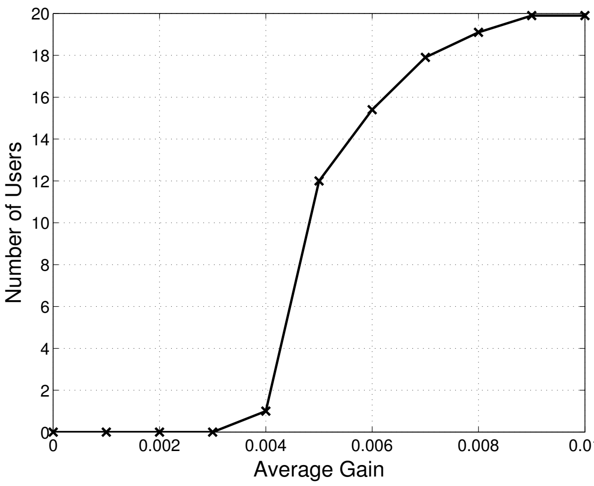


Fig. 2. Number of end-users covered by the SON as a function of the average gain per bandwidth unit, with 20 TPs, 20 DNs and 40 CSs.

d) Effect of the Budget parameter

Finally, in the same scenario we evaluate the effect that a budget constraint has on the planning of a SON, considering several budget (B) values in the range of 500 to 1000 monetary units.

Figure 3 shows the number of end-users covered by the SON as a function of the operator's budget, for different G values.

TABLE IV

SOLUTION PROVIDED BY THE RMSD MODEL WITH 20 TPS AND DNS, 40 CSS AND d_{ik}=500 KB/S

G	N_R	N_L	Revenue	Cost	Time (s)
0.004	1.3	9.7	0.9	51.2	188.7
0.005	15.0	103.0	71.9	623.8	562.5
0.006	17.3	122.4	234.5	786.7	360.7
0.007	18.2	134.0	414.2	896.0	328.1
0.008	18.9	139.6	606.4	951.5	257.9
0.009	19.4	144.4	803.9	990.4	177.8
0.010	19.4	144.4	1003.3	990.4	194.6

For each value of G, as the budget increases, the number of end-users accepted in the network increases until it reaches its maximum, which can be obtained observing Figure 2.

Table V illustrates in details the characteristics of the solutions provided by the RMSD model in such scenario, for $G = 0.005$ monetary units per Mb/s and for different budget values. The results show that deploying higher-cost SONs allows to achieve higher network revenues. However, this also increases the economic risk the SON operator faces in the deployment of the overlay network.

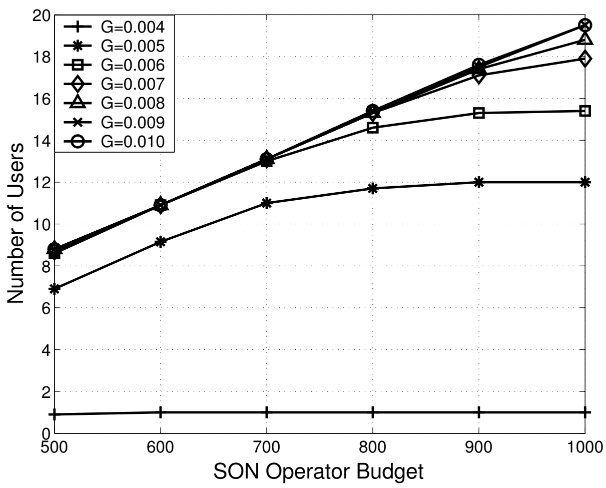


Fig. 3. Number of end-users covered by the SON as a function of the budget for different values of the average gain per bandwidth unit G, with 20 TPs, 20 DNs and 40 CSs.

TABLE V

SOLUTION PROVIDED BY THE RMSD MODEL WITH 20 TPS AND DNS, 40 CSS, G=0.005 MONETARY UNITS PER MB/S AND d_{ik}=500 KB/S

B	N_R	N_L	Revenue	Cost	Time (s)
500	11.6	70.3	45.7	390.4	3743.1
600	12.2	77.8	62.2	464.5	1246.7
700	14.7	97.2	68.6	583.0	926.9
800	15.0	101.6	71.2	613.4	909.1
900	15.0	103.0	71.9	623.8	733.1
1000	15.0	103.0	71.9	623.8	736.0

V. CONCLUSION

In this paper we addressed the issue of topology design for Service Overlay Networks in terms of deciding the number and location of the overlay nodes to be deployed and the capacity reserved on each overlay link.

To this end, we proposed two novel optimization models based on mathematical programming that take into account the individual requirements of the end-users, the connectivity between overlay nodes and the management of the traffic flows.

The objective of the first model is the minimization of the overall network installation cost while assuring full coverage of all end-users. The second model maximizes the SON revenue choosing which users to serve based on the expected gain and budget constraints specified by the SON operator.

To test the quality of the solutions provided by our models, we generated synthetic instances of SONs and solved them to the optimum using AMPL and CPLEX varying several network parameters. The numerical results we gathered show that the models are able to capture the effect on the network topology configuration of all these parameters, providing a promising framework for the design of SONs.

As future research directions, we plan to develop efficient Service Overlay Network design heuristics that could help in the planning of very large-size networks, to support for example periodical SON redesign based on traffic statistics measured online.

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